

The Physics of antineutrinos in DUNE and resolution of octant degeneracy

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Abstract. We study the capability of the DUNE experiment, which will be the first beam based experiment with a wide band flux profile, to uncover the octant of the leptonic mixing angle θ_{23} (i.e., θ_{23} is $< 45^\circ$ or $> 45^\circ$). In this work, we find that for the DUNE baseline of 1300 km, due to enhanced matter effect, the neutrino and antineutrino probabilities are different which creates a tension in the case of combined runs because of which octant sensitivity also can come from disappearance channel. In view of this, we study the physics of antineutrinos in DUNE and explore the role of antineutrinos run that is required to resolve the octant degeneracy at a certain confidence levels.

1. Introduction

The fact that neutrinos have tiny non-zero mass is well established from the various neutrino oscillation experiments and the study of neutrino physics has entered the precision era. The standard 3-flavor neutrino oscillation scenario has six key parameters and these are, two $(mass)^2$ differences ($\Delta m_{i1}^2, i = 2, 3$), three mixing angles ($\theta_{ij}, j > i = 1, 2, 3$) and the CP phase δ_{CP} . Global analysis of neutrino oscillation data provide the best-fit values and 3σ ranges of these parameters and are given in [1, 2, 3]. The remaining unknown in neutrino oscillation physics are (a) the sign of $|\Delta m_{31}^2|$ ($\Delta m_{31}^2 > 0$, known as normal hierarchy (NH) or $\Delta m_{31}^2 < 0$, known as inverted hierarchy (IH)), (b) the octant of θ_{23} ($\theta_{23} < 45^\circ$, known as lower octant (LO) or $\theta_{23} > 45^\circ$, known as higher octant (HO)) and (c) the CP phase δ_{CP} . Information on these unknown parameters can come from the currently running long baseline experiments like T2K [4] and NO ν A [5, 6]. But the main problems which these experiments have to overcome is the issue of parameter degeneracies by which it is meant that different set of parameters can provide equally good fit to the data.

In this letter our main focus is on the resolution of octant degeneracy using next generation superbeam experiment DUNE. Currently, neutrino oscillation experiment, like, T2K gives the most accurate measurements of the parameter θ_{23} . The prime channel for this parameter is the disappearance channel $P_{\mu\mu}$. For baselines shorter than 1000 km this channel has an intrinsic octant degeneracy because of the presence of $\sin^2 2\theta_{23}$ in the leading order term of the probability expression. Whereas the probability expression of $P_{\mu e}$ channel depends on the combination of $\sin^2 \theta_{23} \sin^2 2\theta_{13}$ and hence does not suffer from intrinsic degeneracy but has generalized degeneracies which were addressed in [7, 8, 9, 10, 11]. Here, our main goal is to understand the role of antineutrinos in enhancing the octant sensitivity of DUNE experiment. It was observed

that the main complication that arises in octant determination is due to the unknown value of δ_{CP} in the subleading terms of $P_{\mu e}$ channel which gives rise to octant- δ_{CP} degeneracy. It was discussed in [12, 13] that combining the reactor measurement of θ_{13} with the accelerator data will be beneficial for extraction of information on the octant value from the $P_{\mu e}$ channel. The combined measurement of $P_{\mu\mu}$ channel with $P_{\mu e}$ channel in long baseline experiments can also be helpful in determining the octant degeneracy because of the non-identical functional dependence of the two probabilities on θ_{23} . We present the results of the octant sensitivity using various combinations of (ν and $\bar{\nu}$) run as a function of true δ_{CP} for fixed values of true θ_{23} . In addition, we also present the precision of θ_{23} in (true: θ_{23} - test: θ_{23}) plane. The details of numerical simulation and experimental specifications that we have considered are given in [14] and the references there in.

2. Result

In this section we discuss the octant sensitivity of DUNE experiment. We get four possibilities of (hierarchy-octant) depending on the true parameters and which are, NH-LO, NH-HO, IH-LO and IH-HO. Here, we only discuss the cases NH-LO and IH-LO. Details and the remaining 2 cases are describe in [14]. Here, in the first column dark-blue curves represents True:NH - Test:NH and magenta curves represents True:NH - Test:IH and in the second column dark-blue curves represents True:IH - Test:IH. In both the plots the horizontal yellow line represents the octant sensitivity at 3σ C.L. Representative true value of θ_{23} for this two plots are 39° (LO).

Let consider the case for NH-LO, from the left column of fig.(1) we can see that [10+0] year ν run of DUNE can resolve octant degeneracy at 3σ C.L.(solid blue curve) if the hierarchy is known. The main point to notice here is that, though only neutrino run suffers from octant degeneracy, still we get octant sensitivity around 3σ . This is one of the special features of the on axis beam based neutrino oscillation experiment where the degeneracy does not exist over the complete energy range and one can still have some octant sensitivity only from the neutrino channel. However, storyline changes if the hierarchy is unknown then there is a wrong hierarchy(WH)-wrong octant(WO) solutions in the region $9^\circ < \delta_{CP} < 90^\circ$. We see that once antineutrino run added, say [7+3] years of ($\nu + \bar{\nu}$) run, octant degeneracy can be resolved with more than 4σ C.L. even without the knowledge of the true hierarchy for all values of δ_{CP} .

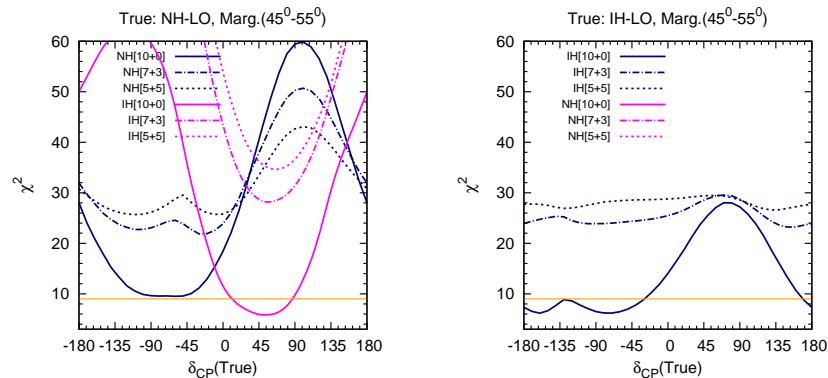


Figure 1. This figures represent octant discovery χ^2 for DUNE. Here, left (right) column is for true NH (IH) and for both the figures true($\theta_{23} = 39^\circ$) and test(θ_{23}) is marginalized over (45° to 55°) and the labels NH and IH inside the plots signifies test hierarchy.

In the case of IH-LO as shown in the right column of fig.(1) when $-180^\circ < \delta_{CP} < 0^\circ$ only neutrino suffers from degeneracy whereas addition of antineutrino run enhances the sensitivity because they do not suffer from octant degeneracy ¹ and hence a large octant sensitive

¹ Note that RHS of fig.(1) does not contain any magenta curve because of the absence of WH-WO solution for IH-LO.

contribution to the χ^2 is added. These combinations of hierarchy–octant can resolve octant degeneracy with 5σ sensitivity with (5+5) years of $(\nu + \bar{\nu})$ run for any value of δ_{CP} .

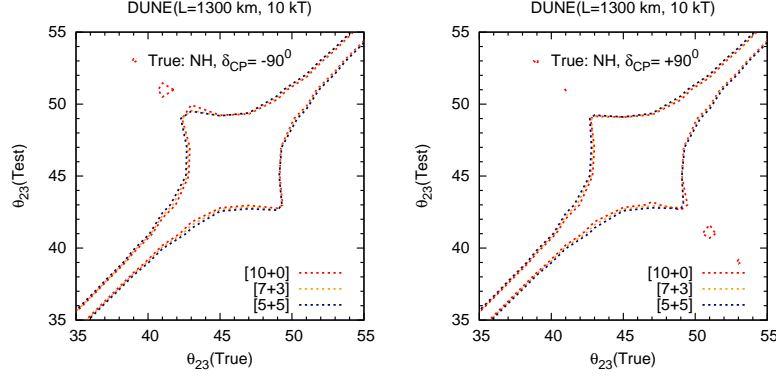


Figure 2. Here, the plots are θ_{23} precision plots of DUNE in $\text{True}(\theta_{23}) - \text{Test}(\theta_{23})$ plane at 3σ C. L. Here both the columns are for NH and left(right) column is for true: $\delta_{CP} = -90^\circ(+90^\circ)$.

In Fig. 2 we plot the 3σ precision contours in the $(\text{true}:\theta_{23} - \text{test}:\theta_{23})$ plane for true $\delta_{CP} = -90^\circ$ (left column) and $\delta_{CP} = +90^\circ$ (right column) for normal hierarchy (for inverted hierarchy see the discussion on [14]). Both these figures demonstrate the relation between precision of θ_{23} and octant degeneracy. From these plots we see that only for neutrino run (i.e (10+0)) there are other allowed values of θ_{23} apart from the true value, if $\theta_{23} \in \text{LO (HO)}$ at $\delta_{CP} = -90^\circ(+90^\circ)$. This happens because of the existence of octant degeneracy. As we have seen from fig.(1) that for $\delta_{CP} = -90^\circ(+90^\circ)$, neutrinos suffer from octant degeneracy in LO (HO) and this in turn affects the precision of θ_{23} which is clearly seen from this figures. Here, we see that the addition of antineutrinos help to improve the precision in both [7+3] and [5+5] curves and both the curves give almost similar precision of θ_{23} . But as one approaches the maximal value of θ_{23} from non-maximal value, the precision becomes worse due to the difficulty in determining the octant around θ_{23} maximal.

In conclusion, we have explored the significant role of antineutrinos in giving an enhanced octant sensitivity in next generation superbeam experiment DUNE which has a 1300 km baseline with a broad-band beam. In our study, we observe that although for some specific parameters only neutrino run can provide 3σ octant sensitivity, overall combined $(\nu + \bar{\nu})$ run gives better sensitivity.

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